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Electric vehicles and the electric grid: A review of modeling approaches, Impacts, and renewable energy integration

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ABSTRACT

Electric vehicles (EVs) and renewable energy sources offer the potential to substantially decrease carbon emissions from both the transportation and power generation sectors of the economy. Mass adoption of EVs will have a number of impacts and benefits, including the ability to assist in the integration of renewable energy into existing electric grids. This paper reviews the current literature on EVs, the electric grid, and renewable energy integration. Key methods and assumptions of the literature are discussed. The economic, environmental and grid impacts of EVs are reviewed. Numerous studies assessing the ability of EVs to integrate renewable energy sources are assessed; the literature indicates that EVs can significantly reduce the amount of excess renewable energy produced in an electric system. Studies on wind–EV interaction are much more detailed than those on solar photovoltaics (PV) and EVs. The paper concludes with recommendations for future research.

Contents

1. Introduction

The world's transportation and electric power generation sectors are directly linked to some of the key driving issues of this century: peak oil, climate change, and energy independence. Electricity generation and transportation account for over 60% of global primary energy demand; a majority of the world's coal demand is for electricity generation and a majority of the world's oil demand is for transportation [1]. Alternative vehicle technologies, such as electric vehicles (EVs), are being developed to reduce the world's dependence on oil for transportation and limit transportation related CO_2 emissions. Likewise, renewable energy

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sources are being developed and deployed to displace fossil fuel based electricity generation, reducing greenhouse gas emissions as well as the emission of other pollutants such as nitrous oxides (NO_x) and sulfur dioxide (SO_2). The integration of the transportation and electricity sectors, in combination with EVs and renewable energy, offers the potential to significantly reduce the world's dependence on fossil fuels and the consequent emission of greenhouse gases.

There are a number of barriers to the large-scale integration of renewables into the electricity system [2]. Renewable energy sources, such as wind and solar photovoltaic (PV) electricity, tend to be variable in supply with no correlation to changes in demand. Whereas natural gas turbines can be ramped up and down to follow fluctuations in demand, renewable energy sources like wind and solar are only available when the wind is blowing or the sun is shining. A variety of strategies have been developed to manage supply fluctuations of varying timescales; these include storage, dispatchable loads (or demand response), and alternative generating capacity [3]. Electric vehicles with an electric grid connection can support all of these strategies; therefore the wide-spread adoption of EVs could play an important role in the integration of renewable energy into existing electricity systems [4].

The basic goal of this paper is to review and assess the literature that discusses the impacts of electric vehicles on the electric grid, with the main focus on the integration of renewable energy into the electricity system. Section 2 gives an overview of EVs, including the key concepts that are pertinent to vehicle interaction with the grid. Section 3 discusses and compares the modeling approaches used in the literature to analyze EVs and the electric grid. Some general impacts and benefits of EVs on the electricity system are presented in Section 4. Section 5 gives a more thorough review of the literature on electric vehicles and renewable energy integration. Section 6 concludes by summarizing the key results of the review and identifying some key knowledge gaps that could inform future research projects.

2. Electric vehicles

2.1. Vehicles and energy sources

An electric vehicle will be defined, for the purposes of this paper, as any vehicle in which some or all of the driving energy is supplied through electricity from a battery. In a conventional internal combustion engine vehicle (ICEV), gasoline or diesel fuel is combusted to create mechanical energy that provides the power to move the vehicle forward. A number of EV technologies are currently in use or under development, as discussed in Jorgensen [5]. A hybrid electric vehicle (HEV) has a small electric battery that supplies electricity to the drivetrain in order to optimize the operating efficiency of the combustion engine. The battery in an HEV can be charged by the engine or through captured kinetic braking energy from a process called regenerative braking. HEVs are more fuel efficient than ICEVs, but ultimately the vehicle is fully powered by liquid fuels. A plug-in hybrid electric vehicle (PHEV) is similar in concept to an HEV, but with a larger battery and a grid connection. The grid connection allows the battery to be charged with electricity and the larger battery size enables the car to drive a significant distance in all-electric mode. An all-electric range of twenty miles can be denoted through the notation PHEV-20, and a forty mile all-electric range would be PHEV-40. A battery electric vehicle (BEV) is fully powered by grid electricity stored in a large onboard battery. EVs use energy much more efficiently than ICEVs; a traditional ICEV fuel efficiency is 15–18%, while a BEV can be as high as 60–70% efficient [5].

Fuel cell vehicles (FCVs) are another type of electric vehicle, in that the fuel cell generates electricity through an electrochemical process in the fuel cell stack. FCVs have an onboard fuel source, such as natural gas or hydrogen, and can either be fully reliant on the fuel cell or designed with a battery in a hybrid arrangement like an HEV or PHEV. Future visions of a hydrogen economy involve the use of FCVs for transportation; if the hydrogen is created through the electrolysis of water using renewable electricity or from biomass sources then the FCVs would be utilizing renewable sources as well. Currently, the vast majority of the world's hydrogen is produced from fossil fuel sources and the creation of a sustainable hydrogen economy still faces a number of hurdles [3]. While hydrogen from electrolysis is an important potential use for renewable electricity, the transition to a hydrogen economy is too broad a topic to be considered in this paper

EV technologies offer opportunities for a transportation sector powered by renewable energy. To the extent that traditional transportation fuels can be replaced by sustainably grown biofuels, such as ethanol or biodiesel, HEVs can be run from renewable energy sources. PHEVs can also use biofuels in their internal combustion engine, while both PHEVs and BEVs can be completely operated with renewables if charged with renewable electricity from the grid. As such, the vehicle technologies that will be considered for this paper are those with the capacity to store electrical energy from the grid: PHEVs and BEVs (from here on referred to jointly as EVs).

2.2. Charging and grid connections

The battery of an electric vehicle can be recharged from the grid with varying measures of external control, labeled here as charge plans. A simple, or unconstrained, charge plan is a system in which the vehicle immediately begins recharging as soon as it is connected to the grid. A delayed charge plan offsets the battery charging by a set amount of time, for example three hours. Nighttime charge plans delay charging to occur over the course of the night when electricity prices are lowest, with the battery fully charged for use in the morning. Smart charging implies some measure of intelligent control over the charging of the vehicle by the utility or system operator. This can either be direct charging, through direct control of the vehicle, or indirect charging by designing the vehicle to respond to price signals. Dallinger and Wietschel [6] suggest that indirect charging is a more promising concept as it is more likely to lead to consumer acceptance than direct external control.

The idea behind smart charging is to charge the vehicle when it is most beneficial, which could be when electricity is at its lowest price, demand is lowest, when there is excess capacity, or based on some other metric. The rate of charge can be varied within certain limits set by the driver; the most basic limit being that the vehicle must be fully charged by morning. Lunz et al. [7] suggest that one focus of smart charging should be to manage battery performance and lifetime, which can improve the lifetime economics of the battery.

A vehicle-to-grid (V2G) capable EV is one that is able to store electricity and then return it to the electric grid. V2G power is an interesting concept that was first proposed by Kempton and Letendre [8]. The authors suggested that V2G could be used to generate a profit for vehicle owners if the power was used under certain conditions to provide valuable services to the electric grid. These services include regulation (second by second balancing of demand and supply), spinning reserve, and peak power provision. The energy could in theory be supplied from the battery of a BEV or PHEV, from the engine of a PHEV in generator mode, or from the fuel cell of an FCV [9]. Pang et al. [10] suggest that vehicle-to-building (V2B) technology is closer to being a viable option than

V2G; under a V2B scenario the EV would offer demand management and outage management services to the building. A V2G/V2B capable EV could store renewably generated electricity during periods of low demand or excess supply and provide it back to the grid, or building, when required.

3. EV-grid models

The body of literature that discusses EVs and the electric grid is primarily based on models, likely due to a scarcity of actual systems of an appropriate size for study. A few single vehicle proof-of-concept tests have been conducted for V2G vehicles [11,12], but no systems level empirical evaluations have been carried out. The models used in the literature can be broadly divided into two categories: (1) long-term, system scale planning models and (2) hourly time-series models.

The long-term planning models are run on a regional or national scale over the course of many decades and generally optimize the mix of electric generating units in a system given a set of boundary conditions, which can include the integration of EVs. Time-series models take hourly historical data of electricity supply and demand as well as driving data in order to assess the ability of the system to match supply and demand over the short and medium term. These models are generally run over the course of one week up to one year.

There are other discussions of EVs and the electricity system that do not involve the use of models, including a review of socio-technical barriers to mass adoption [13], an outline for a transition path and aggregator framework [14] and a discussion of business models and policy options for grid integration [15]. These papers provide insight into the practical considerations for integrating the transportation and electricity sectors. However, at this point in time the most effective way to predict the impacts of EVs on the electrical system is through models; therefore some of the key model inputs and constraints in the literature will now be discussed.

One of the more interesting input variables for the models is the selection of PHEVs versus BEVs. Of the 42 studies that included detailed analysis which were reviewed for this paper, 18 (43%) analyzed PHEVs exclusively, 15 (36%) analyzed BEVs, and 9 (21%) of the studies analyzed both vehicle types. In the PHEV studies, different all-electric ranges could be modeled [16]. In the BEV studies, BEVs were often selected in order to use data and characteristics from actual production vehicles [17,18]. In two of the studies that modeled both BEVs and PHEVs, the models were allowed to endogenously favor vehicle technologies given some optimization constraints; in both cases the models chose PHEVs as preferable to BEVs [19,20]. In a different study, BEVs were assumed to have much lower daily driving ranges than PHEVs [21]. From this, it can be seen that PHEVs are slightly preferred by researchers over BEVs, likely due to lower battery costs and an extended driving range.

The penetration, or market share, of EVs in the models was selected in a number of different ways. A few studies chose a set number of EVs and analyzed the effects of this level of penetration in isolation [4,22]. Others evaluated a range of EV penetration scenarios [21,23]. Goransson et al. [24] took a novel approach, analyzing varying fractions of the total electricity demand that is attributed to EVs. The literature predicting the future market share for EVs offers a wide range of values and scenarios, providing scant insight to modelers on an appropriate penetration level to select [25]. Green et al. [26] suggest that models should have one scenario run with a 0% market share for EVs, which would be considered as a baseline scenario. This could then be compared with multiple EV penetration levels to produce a sensitivity analysis for the effects of EVs.

The influence of charge plans and different charging scenarios is addressed in a number of ways in the literature. Some studies focus exclusively on simple charging [27] or smart charging [16,21]. Others compare just two charging strategies, such as simple charging versus delayed charging [28]. The most prevalent modeling approach is to compare a wide range of charging strategies, with some combination of simple, delayed, nighttime, smart, and smart with V2G being considered [4,23,29].

The availability of accurate and detailed driving patterns is a major issue in the creation of accurate and useful EV/electric grid models [26]. In order to know the available EV storage and discharge capacity at any one time it is necessary to know the number of available (parked and plugged in) vehicles and the amount of energy stored in each battery. The battery energy level, or state-of-charge (SOC), depends on how far the vehicle has been driven since it was fully charged, the vehicle efficiency, and the battery size and characteristics. From a computational perspective it is too difficult to model the driving habits and battery SOC of each individual vehicle, so some models choose to aggregate all the vehicle batteries into one large unit and use historical data to predict vehicle availability [4,23]. Kristofferson et al. [21] state that this method allows the vehicles to charge faster than would actually be realistic; therefore they construct 30 aggregate driving patterns out of historical data in order to more accurately represent the vehicle fleet. Wang et al. [29] aggregate vehicles by size and battery range. Whatever the method, a balance between computational ease and real-world accuracy must be found, and many authors insist that more work must be done to produce accurate vehicle and energy availability functions.

4. EV impacts and performance

There is clearly a wide range of input parameters that can be used for the models, and there is an equally wide range of output variables that the models can measure. The model outputs can be broadly categorized as economic, environmental, grid performance, and renewable energy-related. Some key findings for the first three categories of outputs will be briefly discussed in this section before a more thorough and comprehensive review of studies that focused on the integration of renewable energy into the electricity system is conducted in Section 5.

4.1. Economic impacts

The economic impacts of EVs are generally examined from two perspectives: that of a vehicle owner, and that of the electricity system. The lifecycle economics of EVs are expected to improve with better battery technology and mass production. Currently, BEVs cost more to purchase than PHEVs, and both cost more than traditional ICEVs [30]. However, the fuel and operating costs of EVs are much lower than ICEVs, due to the high efficiency of an electric motor. Thiel et al. [31] estimate that the payback time for a BEV, in comparison to a cheaper ICEV, is currently 20 years, but it should drop to less than five years by 2030. A similar result is found by Faria et al. [32], while Contestabile et al. [33] estimate that the total lifetime costs of ownership for all vehicle types will converge by 2030.

A growing body of studies has assessed the economic viability of V2G participation in different markets [18,34–38]. Yearly profit from these studies ranges from a loss of $300 per vehicle per year to a profit of over $4600, with most indicating a profit in the $100–300 range. This level of profit may not be enough to induce participation, either by individuals or by an aggregator organization. Assuming that both EVs and V2G power services are technologies that governments

want adopted, the question remains of how best to encourage both consumer and business participation in these markets from a policy perspective. This has been discussed for the Ontario, Canada market by Richardson [39].

In general, adding EVs to the electrical grid will increase system costs due to increased fuel use and transmission losses, however the selection of charging strategies greatly influences the overall effect on system costs. Kiviluoma and Meibom [22] estimate a system cost in Denmark of €263/vehicle/year using a simple charge plan, while smart charging vehicles have a system cost of €36/vehicle/year, a savings of €227/vehicle/year. Similarly, Wang et al. [29] conclude that smart charging saves $200,000/week compared to simple charging in a future Illinois electricity system with a high share of wind energy. Lynch et al. [40] calculate the system savings for the PJM and Midwest ISO (MISO) markets in the US, finding that the savings from off-peak charging versus on-peak are highly dependent on the regional generating mix. For the MISO, savings from smart charging are small due to an excess capacity of coal generation, while much larger savings are realized in PJM as this market has a high reliance on more expensive peaking natural gas plants. A study of the Spanish electric grid indicates that the marginal cost of electricity is reduced up to a certain target level of EV penetration, beyond which the marginal cost slightly increases [41].

4.2. Environmental impacts

CO_2 emissions are the most commonly measured output used to assess the environmental impacts of switching to EVs powered by the grid. Juul and Meibom [20] calculate that the integration of the electric power and transportation sectors in Denmark reduces transportation related CO_2 emissions by 85%. Lund and Kempton [4] find that the use of EVs decreases CO_2 emissions compared to ICEVs even if there is no wind energy present in the generation mix. Hadley [28] examines the introduction of EVs in Virginia and the Carolinas in the US where fossil fuel plants account for two-thirds of total generation capacity; even under a simple charge plan EVs reduce CO_2 emissions by roughly 10% compared to the base case with gasoline vehicles. Goransson et al. [24] examine a wind-thermal power system and found that CO_2 emissions slightly increase under a simple charging strategy but decrease with smart charging and V2G power. EVs were analyzed in three regions of China, with CO_2 reductions occurring under all scenarios, even in regions that rely heavily on coal power [42].

There is debate over what emissions intensity (gCO_2e/kWh) should be assigned to the electricity used by electric vehicles when charging. Most studies use the average grid intensity to reflect a situation in which EVs are widely adopted and should be considered as part of the everyday demand profile. Other authors argue for the use of marginal intensity (as discussed in Ma et al. [43]), in which the emissions of the marginal generating unit are assigned to EV electricity. In most markets, especially at times of peak demand, this will be a natural gas or coal power plant which will lead to larger carbon emissions from EVs. However, even studies that utilize the marginal mix in different regions find a net carbon benefit in comparison to the use of ICEVs [44,45]. In general, it can be seen that EVs reduce total CO_2 emissions even in electricity systems with a high fraction of fossil fuel generation, due to the high efficiency of an electric motor in comparison to an internal combustion engine.

4.3. Grid impacts

EVs affect the performance, efficiency, and required capacity of the electric grid, especially if vehicle charging is unconstrained. Hadley [28] found that peak loads will increase under a simple charging strategy, requiring extra investment in generation and transmission capacity. When the vehicles use a smart charging plan, studies indicate that EVs levelize the overall load, make better use of baseload units, and require no extra installed capacity [21,46]. Hajimiragha et al. [47,48] estimate that 500,000 PHEVs that could be introduced in Ontario, Canada without adversely affecting the electric grid. In the US, the existing grid capacity would allow for 73% of the light-duty fleet to be converted to PHEVs [49].

Other impacts of EVs on the distribution grid include increased wear on transformers, transmission bottlenecks and power quality issues; these and other more technical issues are thoroughly reviewed by Green et al. [26]. There are conflicting findings on the effect of EVs on distribution networks. Ma et al. [50] find that EVs and V2G can be controlled in such a way as to have a minimal impact on distribution system losses and voltage fluctuations. Other studies have developed distribution level charge plans designed to maintain power quality and avoid distribution congestion problems that could result from widespread adoption of EVs [51,52]. Gong et al. [53] assess the effects of EVs on a residential distribution transformer; the effects are negligible at low EV penetrations, but there is excess equipment wear with increasing vehicle numbers. A study on UK distribution systems by Papadopolous et al. [54] indicates that high numbers of EVs lead to voltage limit violations, transformer overloads and increased line losses. They suggest that network reinforcements, embedded generation and EV charge management strategies are needed to safely integrate large numbers of EVs into distribution networks.

5. EVs and renewable energy

The ability of EVs to assist the integration of renewable energy sources into the existing power grid is potentially the most transformative impact on the electricity system. The literature on this subject is primarily focused on the analysis of wind energy and solar energy, with wind energy receiving much greater attention and more detailed analysis. A few papers have compared the use of biomass energy for electricity in EVs as opposed to biofuels. The models that study the interaction between renewable energy, generally wind, and EVs tend to measure the amount of renewable capacity that EVs can accommodate, or the effect on system performance that results from integrating EVs into an electricity system with a large fraction of renewable generation. Results from a number of studies on the integration of wind energy and EVs will first be discussed, beginning with a look at the large system scale models and then the hourly time-series models. This is followed by an overview of the work that has been done concerning solar energy and EVs, and a discussion of bioelectricity in comparison to biofuels.

It should be noted that a few papers examine the impacts of EVs on electricity systems with a large share of wind, but the results and discussion are focused on costs [29] or carbon emissions [24], and do not directly address renewable energy integration. As such, these papers are not discussed here.

5.1. Wind energy

A number of studies examine the large-scale, long-term impact of EVs on the ability of electric grids to integrate wind energy. Short and Denholm [16] model the effect of large-scale adoption of PHEVs on the integration of wind energy into the US electricity mix. Installed wind capacity increases by 243 GW, or 6% of total generation, when the vehicle fleet is converted to 50% PHEVs under a smart charging plan.

Turton and Moura [19] use a global energy model that forecasts the integration and impacts of EVs and V2G over the

period from 2000 to 2100. The authors find that the installed renewable energy capacity increases by 30–75% with V2G capable EVs due to their ability to store intermittent energy and discharge it back to the grid when required.

Juul and Meibom [20] examine the integration of the electric power and transportation systems in Denmark for the year 2030 from the perspective of power plant investments. The integration of these two sectors, through the use of EVs, results in a significant increase in offshore wind power capacity and a decrease in combined cycle natural gas plants, biomass electricity plants, and onshore wind power capacity. Overall, the increase in wind power generation exceeds the total demand for energy by the transportation sector.

Borba et al. [55] take an interesting approach to modeling EVs and wind energy. The Brazilian power sector is modeled from 2010 to 2030, with an assumed 16-fold increase in wind generating capacity in the northeast. The authors then calculate the size of PHEV fleet that could be charged using the excess wind energy production. Since the excess production varies seasonally, occurring primarily between January and June, the authors assume that the vehicles drive on locally produced ethanol for the remainder of the year. Over 1.6 million vehicles could be powered in this manner by 2030.

Other studies assess the EV-wind energy interaction on an hourly timescale. Kempton and Tomić [56] evaluate the use of electric vehicles to provide regulation and reserve services in conjunction with wind power in the US. They calculate that in a scenario with 50% power production from wind, 3.2% of the US vehicle fleet would need to be fully electric to provide the required regulation services and 38% of the fleet would be needed to provide operating reserves. The paper also looks at historical time-series wind data from eight dispersed sites in the Midwest. Out of 6919 h of data, they identify 342 low power events where power output would be less than 20% of capacity. BEVs have the ability to provide enough reserve power for events less than two hours in duration, but they cannot cover longer-scale shortages, which can last fourteen to twenty-two hours.

A study by Ekman [23] assesses the relationship between wind energy production, power consumption, and electric vehicle charging patterns in Denmark. Smart charging EVs are found to significantly reduce the excess wind energy generation, with the potential to reduce the required amount of non-wind backup capacity, depending on the vehicle penetration level. The model demonstrates that EVs can be used to aid in the integration of wind energy, but cannot completely make up for intermittent supply from wind.

Lund & Kempton [4] evaluate the integration of wind power and BEVs in national energy systems, in this case Denmark and a hypothetical country identical to Denmark that does not use combined heat and power (CHP) plants. In the CHP case with 50% wind penetration, changing from 100% ICEVs to 100% BEVs with V2G reduces excess wind electricity by a factor of two. The introduction of EVs in the non-CHP system has a larger effect because CHP is more efficient with fuel use and contributes to excess electricity. The study also finds that larger vehicle batteries reduce the amount of excess wind electricity produced.

A paper by Bellekom et al. [57] examines the introduction of wind power and EVs, both separately and combined, in the Dutch electricity system. Four gigawatts of wind can be introduced without problems under the no EV scenario; this increases to 10 GW with the introduction of 1 million EVs. Smart charging is deemed necessary to avoid capacity problems.

A model that coordinates the operation of an EV battery switching station with wind energy production is presented by Gao et al. [58]. Battery switching stations are proposed as a method to extend the range of EVs by replacing depleted batteries with charged batteries. These facilities offer an excellent opportunity for wind energy integration as they would house a large number of battery packs onsite; the battery charging could be managed to account for fluctuations in wind power output.

Hodge et al. [27] simulate electricity supply and demand over a six month summer period in California. The output variable measured is the fraction of power supplied from renewable and wind sources. The results indicate that the addition of V2G has little effect on the fraction of energy supplied by wind, especially as higher penetrations of wind and other renewable sources are reached. This paper uses a 'realistic' scenario, with low levels of PHEV integration and simple charging, which has been shown to be the least effective manner in which to integrate EVs into the grid. It offers no base case with zero PHEV integration, so there is no measure of how PHEVs on their own influence the integration of wind power.

Finally, one of the more detailed and complex studies on EVs and renewable energy is presented by Dallinger and Wietschel [6]. It is the only paper reviewed so far to consider the combination of wind and solar PV, which in a projected German electricity mix comprise 50% of capacity in 2030. The paper examines the influence of charging strategies, but uses an indirect charging strategy based on consumer price response; as such, pooled groups of vehicles must make price forecasts and compare predicted energy costs to vehicle demand. The model also considers grid fees in order to avoid overloading distribution system transformers. The paper finds that EVs can make a positive contribution to balancing renewable sources, with over 50% of the yearly excess renewable production being absorbed by EVs.

Overall, these studies indicate that the introduction of EVs has the potential to increase the amount of wind energy capacity installed in a regional or national electricity system. More specifically, EVs can absorb excess wind energy production that would otherwise be wasted or curtailed, which improves the economics of wind energy generation. The larger the cumulative EV storage capacity, either through more vehicles or larger batteries, the more wind energy that can be accommodated into the system. Furthermore, EVs with V2G power can supply this energy back to the grid, which allows a further integration of wind energy into the generation mix. It should be noted that the marginal benefit of V2G in comparison to the overall benefits of EVs appear to be relatively small.

5.2. Solar energy

The literature on solar energy and EVs is much more diverse than the previously reviewed studies that integrate wind energy and vehicles. Electricity from solar PV can be produced anywhere; this provides more interesting methods to directly integrate energy production and use in EVs. A few representative studies of these varying approaches are discussed. However, it should be noted that the depth of analysis in this field is not nearly as strong as with wind and electric vehicles.

Birnie [59] proposes the idea of solar PV arrays built over parking lots to provide daytime charging to commuter vehicles. The paper broadly sketches out what such a system would look like and assesses the potential energy production from a single parking space. Assuming New Jersey solar irradiation data, a PV module efficiency of 14%, and a 15 m^2 parking space, the average summertime production would be 12.6 kWh and the winter average would be 3.78 kWh. This would be enough to meet most driving needs in the summer, but not during the winter. The paper does not assess the economic practicality of such a system, the utility system benefits, or the environmental benefits.

Li et al. [60] conduct a similar analysis based on data from Alberta, Canada. The authors calculate the size of solar PV panel

needed to provide the daily energy requirements to a PHEV-40. They find that 20 m^2 of panel would be sufficient to provide electricity for 40 miles of range on the best sunshine days in mid-July. However, 78 m^2 of PV panel would be necessary to provide enough electricity in December. The oversized PV panel would produce 67 kWh of excess electricity on the best summer days, which could be sold to the grid to offset the costs of the panel.

Large-scale deployment of parking lot solar car chargers is analyzed by Neumann et al. [61]. This study introduces solar car ports over all the available large parking lots in a medium-sized Swiss city; the authors find that 14–50% of the city's passenger transportation energy demand could be provided through solar energy under the proposed system.

PV parking lot charging and other business models to charge EVs with solar energy are discussed by Letendre [62]. Parking lot chargers could be grid-connected or stand-alone units, sized to meet a daily PV demand. The business models are not analyzed in detail in this paper. Solar PV is estimated to be a cheaper fuel per vehicle kilometer than gasoline, especially as PV module prices decrease and gasoline stays around $4/gallon (USD) or higher.

Gibson and Kelly [63] and Kelly and Gibson [64] examine the technical feasibility of directly charging vehicle batteries with solar PV panels. This would allow EVs to be charged using electricity generated on-site, avoiding transmission losses from distant power plants or wind farms. Furthermore, converting DC solar electricity to AC grid electricity results in energy losses of around 10%; directly charging the batteries from PV panels avoids those losses. These two studies provide a proof of concept for this approach, demonstrating the safety and viability of this charging scheme.

One method of taking advantage of direct battery charging from solar PV would be to combine it with parking lot chargers, as described earlier. Alternatively, PV systems could be mounted directly on the vehicle as an auxiliary power source, also called vehicle-integrated PV (VIPV). This has been done by universities in solar car competitions for years, in which solar energy is the primary power source for the vehicle [65]. Solar cars are not intended for commercial purposes; however VIPV could be used with existing hybrid and electric vehicles to improve efficiency. Letendre [65] estimates this could improve vehicle efficiency by 10–20%, while Giannouli and Yianoulis [66] suggest that the payback time for a VIPV system, in avoided fuel costs, would be just over four years. They also suggest that a VIPV system could be used for other purposes, such as running the vehicle air conditioner to keep the vehicle cool while parked.

Letendre et al. [67] use a very simple method to estimate how much firm capacity a combination of solar PV and V2G-enabled EVs could provide in the California market. The idea is that vehicle batteries would form a short-term buffer for PV output. The calculations do not consider transportation demand or any system analysis.

Kempton and Tomić [56] discuss the use of PV solar electricity to supply peak energy in the US through storage in EVs with V2G power. Peak electricity production from PV panels occurs at mid-day, a few hours before the daily peak in electricity demand. This means that electricity generated at the solar peak would need to be stored for a few hours before use to meet peak demand. Assuming adequate PV capacity to supply all US peak supply (162 GW, or one-fifth of US generating capacity), they estimate that 26% of the US vehicle fleet would be required to store the peak solar electricity and then provide it to the grid a few hours later.

Only one study has been found that employs the more rigourous methodology as the previously discussed studies on wind energy and EVs. Zhang et al. [68] analyze the integration of PV power in conjunction with EVs and heat pumps (HP) in the Kansai Area of Japan. Air source heat pump water heater systems were modeled as a means to meet domestic hot water demand while using excess PV electricity. The study indicates that if 30GW of solar capacity was installed in the area, just over 10 TWh of annual production would be in excess. One million EVs and 1 million HPs could reduce this excess production by approximately 30%, while five million of each could absorb virtually all the excess production. Though HPs were never modeled separately from EVs, the marginal benefit of adding EVs to the system appears to be greater than that of HPs.

5.3. Biomass energy

Biomass energy differs from wind and solar in that it can be stored and used when needed. Liquid biofuels are most commonly proposed for use as an alternative vehicle fuel, but bioelectricity offers a number of advantages over biofuels. Bioelectricity can be obtained using a number of biomass feedstocks, including forestry and agricultural residues, woody energy crops, and whole tree harvesting. These feedstocks can be directly combusted, or co-fired with coal, in a boiler, or they can be gasified into a syngas and used in a simple turbine or combined cycle power plant. Bioelectricity fuel pathways tend to give a higher energy return on energy investment (EROEI) compared to biofuel processes [3].

A number of recent studies indicate that bioelectricity for use in a vehicle is a more effective use of biomass than conversion to biofuels. Schmidt et al. [69] assess the production and use of multiple types of biofuels in Austria compared to bioelectricity; the results indicate that greenhouse gas emissions, land use effects, and the amount of required biomass feed stocks are all reduced using electric vehicles as compared to biofuels. Campbell et al. [70] find that the gross average driving output, in kilometers driven per hectare of biomass production, is 112% greater for bioelectricity than for biofuels. Furthermore, the average net greenhouse gas offset for switchgrass production is 108% greater from bioelectricity than biofuels. Ohlrogge et al. [71] assert that biomass for electricity in EVs displaces twice as much petroleum as biofuels. Electric vehicles using bioelectricity in Ontario, Canada are found to have a higher EROEI, and lower fuel costs and GHG emissions in comparison with ICEVs using biofuels [72]. Thus, given constraints on land availability for biomass production, there is a clear benefit to producing electricity for transportation instead of biofuels.

6. Conclusion

A number of positive impacts can be expected from the introduction of EVs, including lower vehicle operating costs, reduced CO_2 emissions, and the ability to support and contribute to grid power quality and stability if the right infrastructure is adopted. Perhaps most significant, though, is the ability of EVs to assist in the integration renewable energy sources into the electric grid. This has the potential to reduce the carbon emissions from both power generation and transportation. It should be noted that while EVs can substantially reduce some of the negative impacts of large-scale renewable deployment, other methods and technologies are likely necessary to completely integrate a high penetration of renewable energy.

The existing literature is fairly unanimous and conclusive in its assessment that EVs can increase the amount of renewable energy that can be brought online while reducing the negative consequences for the grid. This is better documented, and more conclusive, for wind energy than for solar, as EVs can potentially be charged at off-peak times when otherwise unwanted wind energy can be used to charge the vehicle batteries. This appears to

be the major contribution of EVs under current assumptions. V2G plays a limited role in improving the penetration of renewables in the literature, most likely due to excessive battery degradation which results in a relatively high cost of providing V2G power.

Another common theme that appears in almost every paper on EVs and the grid is the importance of some form of smart charging. Smart charging reduces system costs by avoiding extra investment in peak generating units, transmission and distribution systems. Furthermore, it allows EVs to be used as distributed storage mechanism for absorbing excess renewable energy. While the savings are demonstrable, a comprehensive economic argument in favor of smart chargers has yet to be produced; this topic is worthy of future research. The impacts and interaction between solar energy and EVs is another area requiring detailed analysis, as solar energy charging stations could be a focus on future infrastructure investment.

EVs offer many potential benefits to the electric grid, including the ability to integrate intermittent renewable energy sources. It is important to understand the potential, limits, and impacts of combining the transportation and electricity sectors through EVs and renewable energy. This can inform policies and infrastructure planning in order to maximize the environmental and economic benefits of the two technologies, while at the same time reducing the world's greenhouse gas emissions and its dependence on fossil fuels.

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References

[1] IEA. Key world energy statistics. Paris: International Energy Agency; 2011.
[2] Boyle G, editor. London: Earthscan; 2007.
[3] Harvey LDD. Energy and the new reality 2: carbon-free energy supply. London: Earthscan; 2010.
[4] Lund H, Kempton W. Integration of renewable energy into the transport and electricity sectors through V2G. Energy Policy 2008;36:3578–87.
[5] Jorgensen K. Technologies for electric, hybrid and hydrogen vehicles: electricity from renewable energy sources in transport. Utilities Policy 2008;16:72–9.
[6] Dallinger D, Wietschel M. Grid integration of intermittent renewable energy sources using price-responsive plug-in electric vehicles. Renewable Sustainable Energy Reviews 2012;16:3370–82.
[7] Lunz B, Yan Z, Gerschler J, Sauer D. Influence of plug-in hybrid electric vehicle charging strategies on charging and battery degradation costs. Energy Policy 2012;46:511–9.
[8] Kempton W, Letendre S. Electric vehicles as a new power source for electric utilities. Transportation Research Part D 1997;2:157–75.
[9] Kempton W, Tomić J. Vehicle-to-grid power fundamentals: calculating capacity and net revenue. Journal of Power Sources 2005;144:268–79.
[10] Pang C, Dutta P, Kezunovic M. BEVs/PHEVs as dispersed energy storage for V2B uses in the smart grid. IEEE Transactions on Smart Grid 2012;3(1): 473–82.
[11] Brooks A. Vehicle-to-grid demonstration project: grid regulation ancillary service with a battery electric vehicle. Sand Dimas, CA, California: Air Resources Board and the California Environmental Protection Agency; 2002.
[12] Kempton W., Udo W., Huber K., Komara K., Letendre S., Baker S. et al. A test of vehicle-to-grid (V2G) for energy storage and frequencey regulation in the PJM system. University of Delaware; 2008.
[13] Sovacool B, Hirsch R. Beyond batteries: an examination of the benefits and barriers to plug-in hybrid electric vehicles (PHEVs) and a vehicle-to-grid (V2G) transition. Energy Policy 2009;37:1095–103.
[14] Guille C, Cross G. A conceptual framework for the vehicle-to-grid (V2G) implementation. Energy Policy 2009;37:4379–90.
[15] Andersen P, Mathews J, Rask M. Integrating private transport into renewable energy policy: the strategy of creating intelligent recharging grids for electric vehicles. Energy Policy 2009;37:2481–6.
[16] Short W, Denholm PA. Preliminary assessment of plug-in hybrid electric vehicles on wind energy markets. Golden, CO: National Renewable Energy Laboratory; 2006.
[17] Kempton W, Kubo T. Electric-drive vehicles for peak power in Japan. Energy Policy 2000;28:9–18.
[18] Tomić J, Kempton W. Using fleets of electric-drive vehicles for grid support. Journal of Power Sources 2007;168:459–68.
[19] Turton H, Moura F. Vehicle-to-grid systems for sustainable development: an integrated energy analysis. Technological Forecasting & Social Change 2008;75:1091–108.
[20] Juul N, Meibom P. Optimal configuration of an integrated power and transport system. Energy 2011;36:3523–30.
[21] Kristofferson T, Capion K, Meibom P. Optimal charging of electric drive vehicles in a market environment. Applied Energy 2011;88:1940–8.
[22] Kiviluoma J, Meibom P. Methodology for modeling plug-in electric vehicles in the power system and cost estimates for a system with either smart or dumb electric vehicles. Energy 2011;36:1758–67.
[23] Ekman C. On the synergy between large electric vehicle fleet and high wind penetration—an analysis of the Danish case. Renewable Energy 2011;36:546–53.
[24] Goransson L, Karlsson S, Johnsson F. Integration of plug-in hybrid electric vehicles in a regional wind-thermal power system. Energy Policy 2010;38:5482–92.
[25] Oak Ridge National Laboratory. A comparative study of emerging vehicle technology assessments. Oak Ridge, TN: Oak Ridge National Laboratory; 2011.
[26] Green R, Wang L, Alam M. The impact of plug-in hybrid electric vehicles on distribution networks: a review and outlook. Renewable Sustainable Energy Review 2011;15:544–53.
[27] Hodge B, Huang S, Shukla A, Pekny J, Reklaitis G. The effects of vehicle-to-grid systems on wind power integration in California. Computer Aided Chemical Engineering 2010;28:1039–44.
[28] Hadley S. Impact of plug-in hybrid vehicles on the electric grid. Oak Ridge, TN: Oak Ridge National Laboratory; 2006.
[29] Wang J, Liu C, Ton D, Zhou Y, Kim J, Vyas A. Impact of plug-in hybrid electric vehicles on power systems with demand response and wind power. Energy Policy 2011;39:4016–21.
[30] Thomas C. Fuel cell and battery electric vehicles compared. International Journal of Hydrogen Energy 2009;34:6005–20.
[31] Thiel C, Perojo A, Mercier A. Cost and CO_2 aspects of future vehicle options in Europe under new energy policy scenarios. Energy Policy 2010;38: 7142–51.
[32] Faria R, Moura P, Delgado J, de Almeida A. A sustainability assessment of electric vehicles as a personal mobility system. Energy Conversion and Management 2012;61:19–30.
[33] Contestabile M, Offer G, Slade R, Jaeger F, Thoenees M. Battery electric vehicles, hydrogen fuel cells and biofuels. Which will be the winner? Energy & Environmental Science 2011;4:3754–72.
[34] Andersson SL, Elotsson A, Galus M, Göransson L, Karlsson S, Johnsson F, et al. Plug-in hybrid electric vehicles as regulating power providers: case studies of Sweden and Germany. Energy Policy 2010;38:2751–62.
[35] Quinn C, Zimmerle D, Bradley T. The effect of communication architecture on the availability, reliability, and economics of plug-in hybrid electric vehicle-to-grid ancillary services. Journal of Power Sources 2010;195:1500–9.
[36] Peterson S, Whitacre J, Apt J. The economics of using plug-in hybrid electric vehicles battery packs for grid storage. Journal of Power Sources 2010;195:2385–92.
[37] Sioshansi R, Denholm P. The value of plug-in hybrid electric vehicles as grid resources. The Energy Journal 2010;31:1–23.
[38] White C, Zhang K. Using vehicle-to-grid technology for frequency regulation and peak-load reduction. Journal of Power Sources 2011;196:3972–80.
[39] Richardson D. Economic analysis of vehicle-to-grid (V2G) business models and tariff structures in Ontario, Canada. Energy Policy. p. 32, submitted for publication.
[40] Lynch T, Michelin M, Jongejan A, Leahy T. Is smart charging policy for electric vehicles worthwhile? Energy Policy 2012;41:259–68.
[41] Fernandes C, Frías P, Latorre J. Impact of vehicle-to-grid on power system operation costs: the Spanish case study. Applird Energy 2012;96:194–202.
[42] Wu Y, Yang Z, Lin B, Liu H, Wang R, Zhou B, et al. Energy consumption and CO_2 emission impacts of vehicle electrification in three developed regions of China. Energy Policy 2012;48:537–50.
[43] Ma H, Balthser F, Tait N, Riera-Palou X, Harrison A. A new comparison between the life cycle greenhouse gas emissions of battery electric vehicles and internal comubstion vehicles. Energy Policy 2012;44:160–73.
[44] McCarthy R, Yang C. Determining marginal electricity for near-term plug-in and fuel cell vehicle demands in California: impacts on vehicle greenhouse gas emissions. Journal of Power Sources 2010;195:2099–109.
[45] Elgowainy A, Burnham A, Wang M, Molburg J, Rousseau A. Well-to-wheels energy use and greenhouse gas emissions analysis of plug-in hybrid electric vehicles. Lemont, IL: Argonne National Laboratory; 2009.
[46] Denholm P, Short W. An evaluation of utility system impacts and benefits of optimally dispatched plug-in hybrid electric vehicles. Golden, CO: National Renewable Energy Laboratory; 2006.
[47] Hajimiragha A, Cañizares C, Fowler M, Elkamel E. Optimal transition to plug-in hybrid electric vehicles in Ontario, Canada, considering the electricity-grid limitations. IEEE Transactions on Industrial Electronics 2010;57:690–701.
[48] Hajimiragha A, Cañizares C, Fowler M, Moazeni S, Elkamel A. A robust optimization approach for planning the transition to plug-in hybrid electric vehicles. IEEE Transactions on Power Systems 2011;26:2264–74.

[49] Kintner-Meyer M, Scheider K, Pratt R. Impacts assessment of plug-in hybrid vehicles on electric utilities and regional U.S. power grids part 1: technical analysis. Richland, WA: Pacific Northwest National Laboratory; 2007.
[50] Ma Y, Houghton T, Cruden A, Infield D. Modeling the benefits of vehicle-to-grid technology to a power system. IEEE Transactions on Power Systems 2012;27(2):1012–20.
[51] Sundstrom O, Binding C. Flexible charging optimization for electric vehicles considering distribution constraints. IEEE Transactions on Smart Grid 2012;3(1):26–37.
[52] Richardson P, Flynn D, Keane A. Local versus centralized charging strategies for electric vehicles in low voltage distribution systems. IEEE Transactions on Smart Grid 2012;3(2):1020–8.
[53] Gong Q, Midlan-Mohler S, Marano V, Rizzoni G. Study of PEV charging on residential distribution transformer life. IEEE Transactions on Smart Grid 2012;3(1):404–12.
[54] Papadopolous P, Skarvelis-Kazakos S, Grau I, Cipcigan L, Jenkins N. Electric vehicles' impact on British distribution networks. IET Electrical Systems in Transportation 2012;2(3):91–102.
[55] Borba B, Szklo A, Schaeffer R. Plug-in hybrid electric vehicles as a way to maximize the integration of variable renewable energy in power systems: the case of wind generation in northeastern Brazil. Energy 2012;37:469–81.
[56] Kempton W, Tomić J. Vehicle-to-grid power implementation: from stabilizing the grid to supporting large-scale renewable energy. Journal of Power Sources 2005;144:280–94.
[57] Bellekom S, Benders R, Pelgröm S, Moll H. Electric cars and wind energy: two problems, one solution? A study to combine wind energy and electric cars in 2020 in The Netherlands. Energy 2012;45(1):859–66.
[58] Gao Y, Zhao K, Wang C. Economic dispatch containing wind power and electric vehicle battery swap station. In: Proceedings of the IEEE power engineering society transmission and distribution conference; 2012. p. 1–7.
[59] Birnie D. Solar-to-vehicle (S2V) systems for powering commuters of the future. Journal of Power Sources 2009;186:539–42.
[60] Li X, Lopes L, Williamson S. On the suitability of plug-in hybrid electric vehicles (PHEV) charging infrastructure based on wind and solar energy. In: Proceedings of the IEEE power & energy society general meeting; 2009.
[61] Neumann H, Schär D, Baumgartner F. The potential of photovoltaic carports to cover the energy demand of road passenger transport. Progress in Photovoltaics: Research and Applications 2012;20:639–49.
[62] Letendre S. Solar electricity as a fuel for light vehicles. In: Proceedings of the 2009 American solar energy society annuual conference, Boulder, CO; 2009.
[63] Gibson T, Kelly N. Solar photovoltaic charging of lithium-ion batteries. Journal of Power Sources 2010;195:3928–32.
[64] Kelly N, Gibson T. Solar photovoltaic charging of high voltage nickel metal hydride batteries using DC power conversion. Journal of Power Sources 2011;196:10430–41.
[65] Letendre S. Vehicle integrated photovoltaics: exploring the potential. In: Proceedings of the 23rd annuual electric vehicles symposium. Anaheim, CA; 2007.
[66] Giannouli M, Yianoulis P. Study on the incorporation of photovoltaic systems as an auxiliary power source for hybrid and electric vehicles. Solar Energy 2012;86:441–51.
[67] Letendre S, Perez R, Herig C. Battery-powered electric-drive vehicles providing buffer storage for PV capacity value. In: Proceedings of the 2002 American solar energy society annual conference. Boulder, CO; 2002.
[68] Zhang Q, Tezuka T, Ishihara K, Mclellan B. Integration of PV power into future low-carbon smart electricity systems with EV and HP in Kansai Area, Japan. Renewable Energy 2012;44:99–108.
[69] Schmidt J, Gass V, Schmid E. Land use changes, greenhouse gas emissions, and fossil fuel substitution of biofuels compared to bioelectricity production for electric cars in Austria. Biomass Bioenergy 2011;35:4060–74.
[70] Campbell J, Lobell D, Field C. Greater transportation energy and GHG offsets from bioelectricity than ethanol. Science 2009;324:1055–7.
[71] Ohlrogge J, Allen D, Berguson B, DellaPenna D, Schachar-Hill Y, Stymme S. Driving on biomass. Science 2009;324:1019–20.
[72] Richardson D. A comparison of biomass energy sources and fuel pathways for vehicles: an Ontario, Canada case study. Energy Sources Part A. p. 16, http://dx.doi.org/10.1080/15567036.2012.721861, in press.